PCGEOFIM – Integrated Modelling of Mining specific Groundwater Dynamics and Soil Water Budget

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Abstract

Post-mining areas in Central Germany are characterized by pit lakes. Therefore, the impact of the expected change of land use may be considerable because changes in groundwater recharge patterns and a possible increase of evaporation from lakes can be important for the total water budget.

A coupled groundwater and soil water budget model based on the groundwater simulator PCGEOFIM and the soil water budget model ArcEGMO was developed. The groundwater model supplies groundwater levels and base flow; the soil water budget model groundwater recharge and river discharge. The exchange time step is typically one day. The model was successfully applied to a site in Central Germany. Model results presented here show good agreement with measured values and first predictions were made. In consideration of the effects of climate change, the model results will have great importance for planning of activities in the region such as recreational use.

Key words: PCGEOFIM, ArcEGMO, groundwater, soil water budget, coupled modeling

Introduction

The complex processes of the water balance can be examined only by models which represent the system in an adequate manner. During the last decades several sophisticated and mature numerical models were created to describe specific parts of the water balance sufficiently. However, for the complex interactions between the different water budget components especially in mining and post-mining areas, their separated consideration is not sufficient for reliable results. Therefore, two separate models, the groundwater simulator PCGEOFIM and the soil water budget model ArcEGMO, were coupled in a bi-directional way.

Groundwater simulator PCGEOFIM

PCGEOFIM (Mansel et al. (2011)) is a numerical groundwater modeling system. It uses the Finite-Volume method to simulate groundwater flow and solute transport. Being developed for more than 25 years, it provides special features to account for mining-related demands and conditions.

Subsurface parameters can be specified as time-dependent to allow for the modeling of excavation of pit mines, filling with overburden, and creation of pit lakes within a single simulation run (Blankenburg et al. (2013)). While working with a regular grid, multiple nested grid refinements that may overlap can be used to get higher resolution in regions of special interest.

In the scope of opencast mining activities and post-mining areas, open pit lakes and surface water such as rivers play an important role in the water management. PCGEOFIM provides a simple but very useful mechanism to account for the interactions between lakes and groundwater. All inflows such as precipitation, groundwater and river infiltration or exfiltration are balanced for each lake. The water level of the lake is computed from a water level-volume relationship which in turn is derived from the spatial geometry (mold) of the lake. That water level is taken as value for the third type boundary condition and is assigned to all cells related to the lake. That relationship is established via vertical and horizontal coupling schemes and is presented in fig. 1.

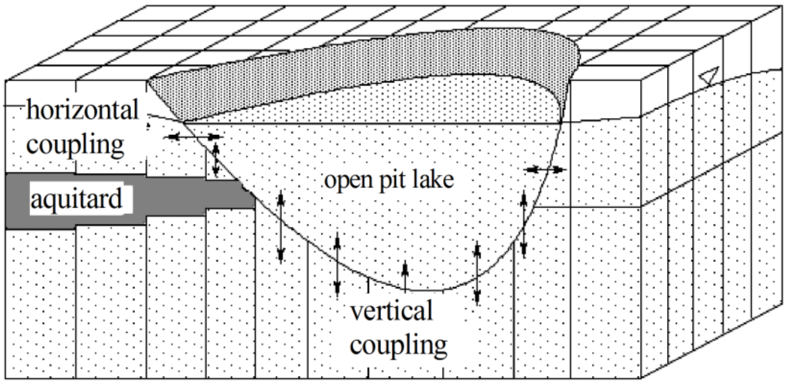

***Figure 1** Implementation of the boundary condition "lake" in PCGEOFIM*

Rivers are represented in a similar manner by using again a third type boundary condition. The flow rate is calculated according to Manning-Strickler's method. In combination with a flow rate-water level relationship the river water level is determined and used as value for the third type boundary condition for each section of the river.

There are a number of additional specific boundary conditions such as wells and HDD-wells across several groundwater layers or controllable connections between rivers and lakes. These connections allow for the implementation of overflows in dependency of user defined conditions. The groundwater recharge rate can be defined in numerous ways with increasing complexity, starting from simply time-invariant or time-dependent, continuing with being a function of the locality, depth to water table in combination with land use and time. In case of coupled modeling, PCGEOFIM gets the groundwater recharge rate from the soil water budget model ArcEGMO.

Soil water budget model ArcEGMO

ArcEGMO (Becker et al. (2002)) is a GIS-based hydrological modeling system. It simulates the spatially distributed hydrological processes in river catchments on different scales. The model consists of two domains:

- Discharge formation which represents the vertical oriented processes and which depends of meteorological parameters as well as vegetation and land use parameters
- Discharge concentration which represents the horizontal processes such as surface runoff or channel discharge, and base flow

In addition to the usual model approaches for describing the lateral surface and subsurface water flows at river basin scales (Becker et al. (2002)), it contains complex growth models for forest and agricultural areas and a detailed soil model (water, carbon/ nitrogen budget). Through implementation of a crop rotation generator, the agricultural land use structure of a region can be well reproduced. Air temperature, precipitation, humidity and global radiation in daily resolution are the required climatic driving variables.

The model domain is discretized in hydrotopes. Hydrotopes are areas with similar or identical hydrological properties, land use, topography, and soil profile. Vegetation dynamics are simulated in dependence on land use in the individual hydrotopes. Four different plant models have been integrated into the model. The groundwater component in ArcEGMO is realized as a linear storage with constant groundwater level. In case of a coupled modeling this groundwater component is deactivated and the groundwater table is imported from PCGEOFIM.

Coupled groundwater and soil water budget modeling

To account for the feedbacks between soil water budget, recharge and groundwater table a bi-directional (online) coupling of the two previously described models PCGEOFIM and ArcEGMO was developed. Figure 2 shows the schematic of the exchange between both models. The groundwater simulator PCGEOFIM supplies groundwater levels and base flow and the soil water budget model ArcEGMO supplies recharge and river discharge. Furthermore, flows at model boundaries are also exchanged if the model domains are not of equal size.

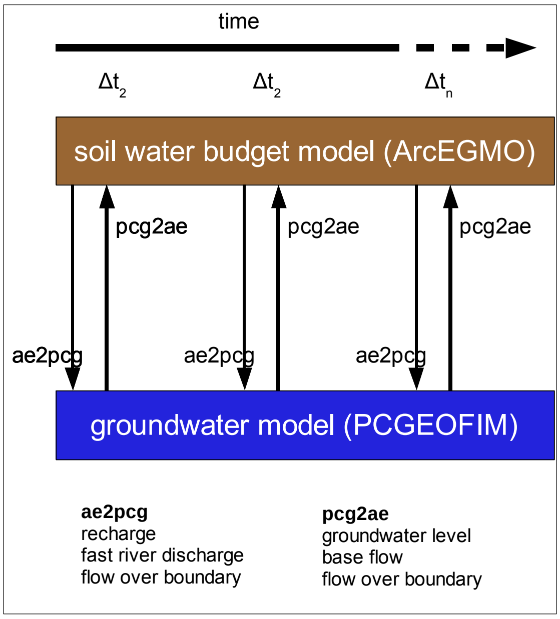

Figure 2 *Schematic of the coupling. The Term ae2pcg characterizes the direction from ArcEGMO to PCGEOFIM; pcg2ae refers to the opposite direction*

All quantities are exchanged with a variable time step that is determined by internal numerical criteria. Time steps will get smaller if river discharge is high. The maximum specific time step is typically one day, which allows for an intensive feedback between both models.

The flow over boundaries in fig. 2 regards to the river discharge that is handed in from the spatially larger model at the boundary to the smaller model. That allows for the modeling of areas where surface and subsurface catchments may not correspond. Climatic changes can be considered directly because ArcEGMO uses meteorological data as input and therefore reacts to changes in climatic conditions.

Soil layers in the soil water budget and groundwater model are of the same size and have the same parameters. If a layer is unsaturated, it will be part of the soil water budget model. As soon as it becomes saturated, it will become part of the groundwater model. That means there is a spatially moving interface between the two models. If the groundwater level reaches the soil surface, all layers will be part of the groundwater model. Groundwater that seeps out at the surface will be put in a surface storage from where it can evaporate or flow into the next river if the storage capacity is exceeded.

Application of the coupled model

The coupled model has been applied to a site in Central Germany in the area of Nachterstedt (IBGW GmbH (2008)). Opencast mining activities lasted from the 19th century to the mid-nineties. The flooding of the open pit lakes began in 1998 by rising groundwater table and supplying of fluvial water. The domain of the groundwater model, colored in green in fig. 3, has an area of 150 km² and incorporates the former opencast pit. The main gaining stream Selke traverses the region from South East to North West. The domain of the soil water budget model has an area of 300 km². It is depicted in orange color in fig. 3.

The discretization step width of both, the groundwater and soil water budget model, was chosen to be identical so that each cell of the top layer of the groundwater model has a corresponding soil budget water cell. Furthermore, the upper two meters of the subsurface are part of both, the groundwater simulator and the soil water budget model, to account for the fluctuating groundwater table.

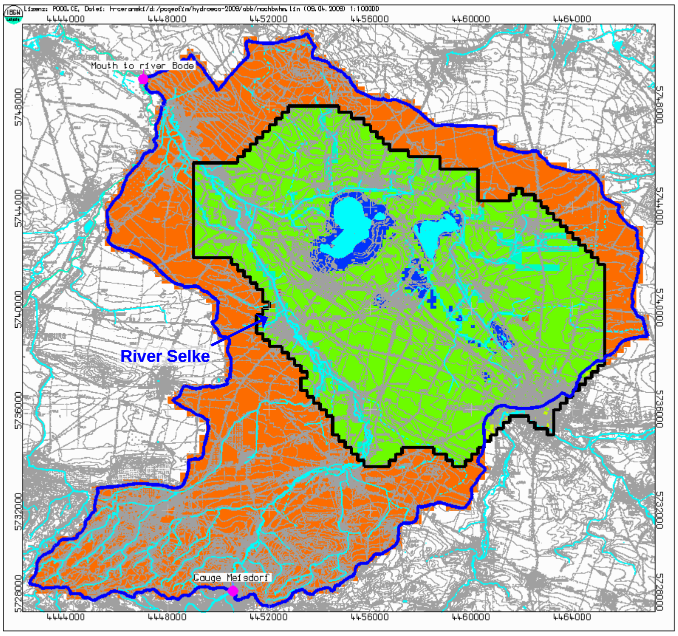

Figure 3 *Groundwater (green) and soil water budget (orange) model domain of site Nachterstedt*

As shown in fig. 3, the extent of the model domain of the soil budget and the groundwater simulator are different. The soil water budget model covers a greater area than the groundwater model. The cyanic areas refer to open pit lakes and rivers. The flow data of the rivers crossing the boundaries between the models are also exchanged at each time step. An exchange time step of one day proved to be useful and allowed stable calculations.

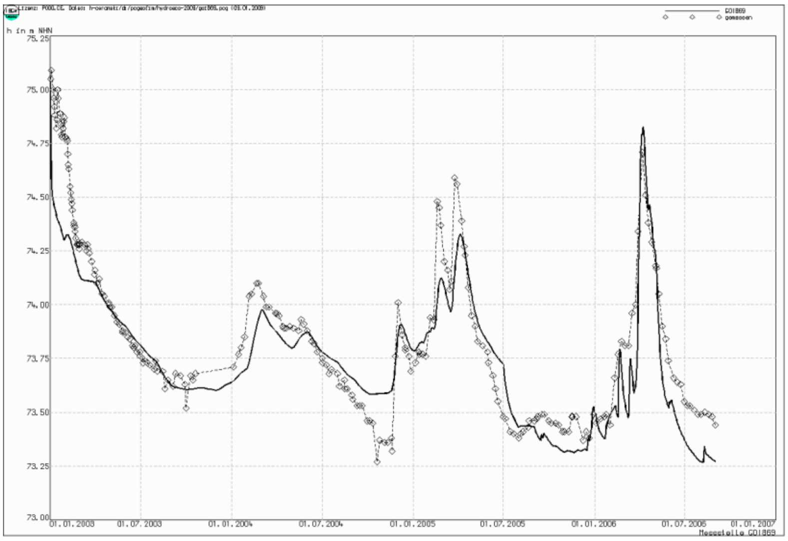

Figure 4 *Comparison of measured and calculated groundwater level at a gauge in the vicinity of the river Selke*

Model runs were carried out in three phases. After a calibration period, the model was run with constant boundary conditions until it reached steady state conditions. Finally, a prediction calculation was done for 25 years starting from steady state conditions. The models could reproduce measured values of groundwater levels and river discharges with good accuracy. Especially in regions with shallow groundwater levels and thus strong interactions between groundwater and soil water significant improvements of model representations could be achieved. Fig. 4 shows good agreement between modeling results and measured values for an observation well close to a river.

Fig. 5 shows the significant change of recharge patterns at the beginning (left) and at the end (right) of the pit flooding. The average groundwater recharge rate is reduced for 23 % (from 53 to 41 mm/a), firstly, due to the conversion of land area into lake area and, secondly, due to shallow groundwater tables where evapotranspiration is increased. The change of the evapotranspiration patterns is shown in fig. 6. Here, the average evapotranspiration increases about 18 % (from 464 to 548 mm/a).

That development of the water balance has negative consequences on the water management of the region. The lakes feed the surrounding streams. The negative water balance leads temporarily to zero-flow rates in some streams, especially in the summer months destabilizing the sensitive hydro ecology of the area. On the other hand, the rising groundwater table causes the formation of shallow surface water bodies interfering with the current agricultural use.

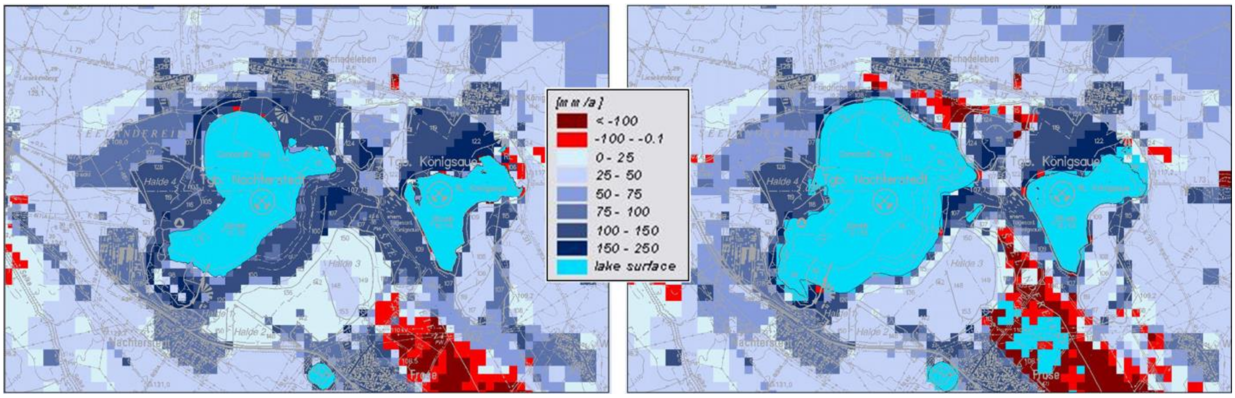

Figure 5 *Comparison of recharge patterns during (left) and after (right) pit flooding*

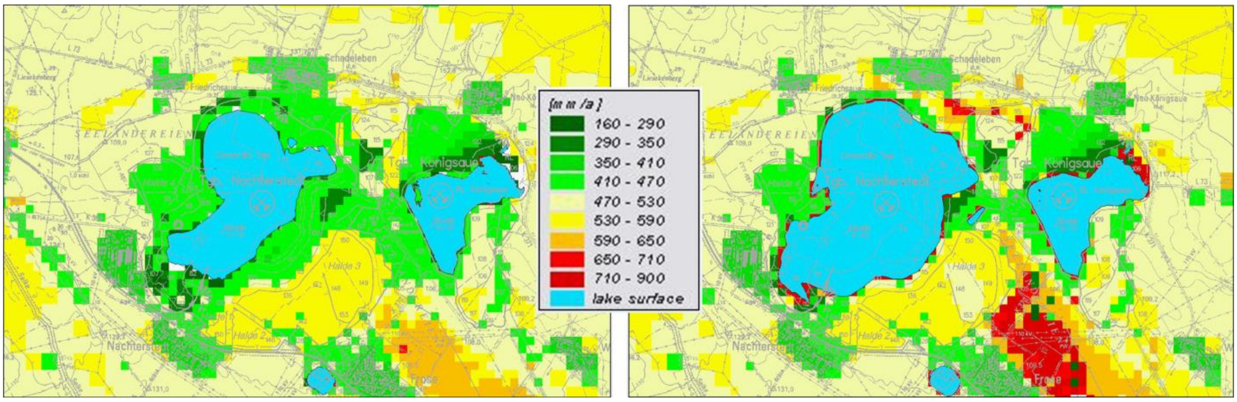

Figure 6 *Comparison of evapotranspiration pattern during (left) and after (right) pit flooding*

Conclusions

The coupled model has proved to be an effective tool for the determination of water management measurements, especially in the case of strong interactions between groundwater and surface waters. Because of the direct processing of climatic data with the coupled model, regionalized data from climate models can be used immediately. By means of scenario runs with the coupled model, different climatic conditions can be simulated and the results are available for statistical analyses. The strong seasonal and long-term volatility of the water balance at the Nachterstedt site in combination with distinctive droughts and wet periods emphasizes the importance of results of the coupled modeling.

In summary, the change of landscape in Central Germany caused by mining activities has a great impact on land use and water management systems. That has to be accounted for by coupled groundwater and surface water modelling. Further investigations of the impact of the climate change are necessary, especially in that region.

References

Becker, A., Klöcking, B., Lahmer, W., Pfützner, B. (2002) The Hydrological Modelling System ArcEGMO. In: Mathematical Models of Large Watershed Hydrology (Eds.: Singh, V.P. and Frevert, D.K.). Water Resources Publications, Littleton/Colorado, 321-384. ISBN 1-887201-34

Blankenburg, R., Mansel, H., Sames, D., Brückner, F. (2013) Consideration of Open Cast Mining Progress and more using the Finite Volume Model PCGEOFIM, In: Maxwell, Hill, Zheng and Tonkin: Conference Proceedings of MODFLOW and More, Golden, Colorado

IBGW GmbH (2008) Aufbau eines Bodenwasserhaushaltsmodells für das Gebiet Aschersleben-Nachterstedt, Phase 3: Gekoppelte Modellierung, Leipzig

Mansel, H. et al. (2011) PCGEOFIM® als bewährtes Werkzeug zur Prognose des GW-Wiederanstiegs in den Bergbaufolgelandschaften Mitteldeutschlands und der Lausitz. In: Proceedings der Grundwassertage, Band 45